IceCube Realtime HESE - AMON - GCN Public Document

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1 Established Results

The IceCube high-energy starting event (HESE) search resulted in a clear detection ($> 6.5\sigma$) of cosmic neutrinos [1, 2, 3]. However, the nature of the sources responsible for these neutrinos is not yet known. The sources of cosmic neutrinos may be identified by rapid follow-up observations by electromagnetic observatories. Discovery of even a single multimessenger counterpart of a cosmic neutrino would revolutionize our understanding of the high-energy universe: the longstanding questions concerning the origin of cosmic neutrinos, and potentially also the composition of cosmic rays, could be finally resolved.

IceCube has detected 54 HESE neutrino candidates in 4 years of data collection. These events have interaction vertices inside the detector fiducial volume and are classified in two main categories: track-like events from charged-current interactions of muon neutrinos (and from about one in five tau neutrino interactions) and shower-like events from all other interactions (neutral-current interactions and charged-current interactions of electron neutrinos and most tau neutrinos). The HESE data is dominated by shower-like events. In the 4-year data sample, there are 14 track-like events and the rest are shower-like events. Shower-like events have an angular uncertainty of about 15° whereas track-like events have a resolution better than 1°. However, these numbers are only attained by time-consuming offline reconstructions. The resolutions obtained in real time are somewhat worse. **In this**

document, we only discuss the track-like events, as these are the events now being publicly distributed. Their related parameters are explained in more detail below.

2 GCN Alert Contents

Here we describe the information contained in GCN alerts from the HESE data stream (containing only track-like events) that will be sent to the follow-up observatories via AMON. GCN alerts can be received in email, VOEvent and/or socket-based format. Here we describe all the parameters that a follow-up observatory will receive via email in Table 1. The key parameters are the same in the other formats.

Table 1: GCN alert contents. [a]TJD = Truncated Julian Date, [b]DOY = Days of Year, [c]SOD = Seconds of Day in units of centi-seconds (seconds multiplied by 100 and then integerized).

Parameter	**Description**	**Unit**	**Comments**
TITLE	"GCN/AMON Notice"		
NOTICE_DATE	GCN notice time	UT	
NOTICE_TYPE	"AMON ICECUBE HESE"		
RUN_NUM	IceCube HESE Run ID		
EVENT_NUM	IceCube HESE Event ID		
SRC_RA	Right Ascension of the event	J2000, current, and 1950	
SRC_DEC	Declination of the event	J2000, current, and 1950	
SRC_ERROR50	Angular error of the event with 50% containment	arcmin radius	Varies between 0.4° and 1.6° for revision-0 based on the event properties, see Section 7
SRC_ERROR	Angular error of the event with 90% containment	arcmin radius	Varies between 1.2° and 8.9° for revision-0 based on the event properties, see Section 7

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Table 1 – *Continued from previous page*

Parameter	**Description**	**Unit**	**Comments**
DISCOVERY_DATE	Event arrival date	TJD[a] and DOY[b] and (yy/mm/dd)	
DISCOVERY_TIME	Event arrival time	SOD[c] and UT	
SAME_AS_EHE	This parameter describes whether a given alert is due to the same neutrino event (same run number and same event number) as a previous alert from another (EHE) stream or unique.	N/A	0 if alert is unique, 1 if it is dual with an alert from EHE stream. Most of the time alert will be unique (i.e. value of 0).
REVISION	Revision number of this HESE alert		See Section 3
N_EVENTS	Number of neutrinos, always 1 for HESE stream	TJD	
STREAM	Stream number (=1 for HESE)		
DELTA_T	0 for HESE	[sec]	
SIGMA_T	0 for hESE	[sec]	
FALSE_POS	False positive rate density (background density) in the vicinity of the event	[$s^{-1}sr^{-1}$]	This parameter is not available for revision-0 alerts [value of 0 means N/A]
PVALUE	Chance probability of being an atmospheric neutrino. Low p-value ($p < 0.0027$ (3σ)) indicates a given alert is less likely to be background	[dn]	This parameter is not available for revision-0 alerts [value of 0 means N/A]
CHARGE	Total deposited charge in the IceCube detector (Detected Cherenkov photons are converted to charge by PMTs.)	[p.e.]	Only if > 6000 p.e., see Section 4
SIGNAL_TRACKNESS	This estimator is a number between 0 and 1, showing how likely an event is signal-like and track-like		Only if > 0.1, see Section 5
SUN_POSTN	(RA, Dec) of the Sun	[deg] and ([h,m,s],[d,,])	

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Table 1 – *Continued from previous page*

Parameter	Description	Unit	Comments
SUN_DIST	Angular distance of the event relative to the Sun	[deg]	Also Sun_angle in [hr] (East of Sun)
MOON_POSTN	(RA, Dec) of the Moon	[deg] and ([h,m,s],[d,,])	
MOON_DIST	Angular distance of the event relative to the Moon	[deg]	
GAL_COORDS	Galactic longitude and latitude of the event	[deg]	
ECL_COORDS	Ecliptic longitude and latitude of the event	[deg]	
COMMENTS	"AMON_ICECUBE _HESE"	[deg]	

3 Potential Revisions

The event reconstruction may be refined in near realtime (within three hours of an original alert) with a better angular reconstruction and a better distinction between track-like and shower-like events. These refined reconstructions will improve angular resolution by more than 50% ($\leq 1°$). When this happens, a revised alert that contains new information will be created. The revised alert will keep the same event number information as the original alert, but it will have its revision number increased by 1. The revision is 0 for the first realtime alert and will be increased by 1 for each new event revision. Each alert can be revised multiple times.

3.1 Retractions

Any alert that is determined not to be astrophysical in origin will be retracted within hours or possibly up to a day following the original alert.

4 Charge

The astrophysical signal is most prominent at high energy where neutrino interactions result in lots of light (and photoelectrons or 'charge') in the detector. We use the charge most causally connected (observed within 5 μs of the event start time) in order to cut out light from combined low energy events. All hits in DeepCore and on single digital optical modules (DOMs) containing more than 50% of the total charge in the event are excluded. **Here, we distribute HESE with charges $\geq$ 6000 p.e.**

5 Signal_Trackness

This estimator is a number between 0 and 1, characterizing how likely a HESE event is both signal-like as well as track-like. To find this number, Monte Carlo simulations including both signal and background events have been considered. Signal events have been simulated with an $E^{-2.58}$ spectrum, approximately the best-fit measured astrophysical spectrum. A Bayesian approach has been taken into account to calculate the probability that a HESE event is a track-like signal event:

$$\text{Signal\_Trackness} = \frac{f_{\text{track}} P_{\text{track}}}{f_{\text{track}} P_{\text{track}} + f_{\text{shower}} P_{\text{shower}} + f_{\text{bkg}}/f_{\text{sig}} P_{\text{bkg}}}, \tag{1}$$

where P_{track}, P_{shower}, and P_{bkg} are the probability density functions (PDFs) of log-likelihood ratios (value from the shower reconstruction divided by that of the track reconstruction) for track-like events, shower-like events, and backgrounds, respectively. The variables f_{track}, f_{shower}, f_{bkg}, and f_{sig} are the prior probabilities, and $f_{\text{track}} = 1 - f_{\text{shower}}$ and is equal to:

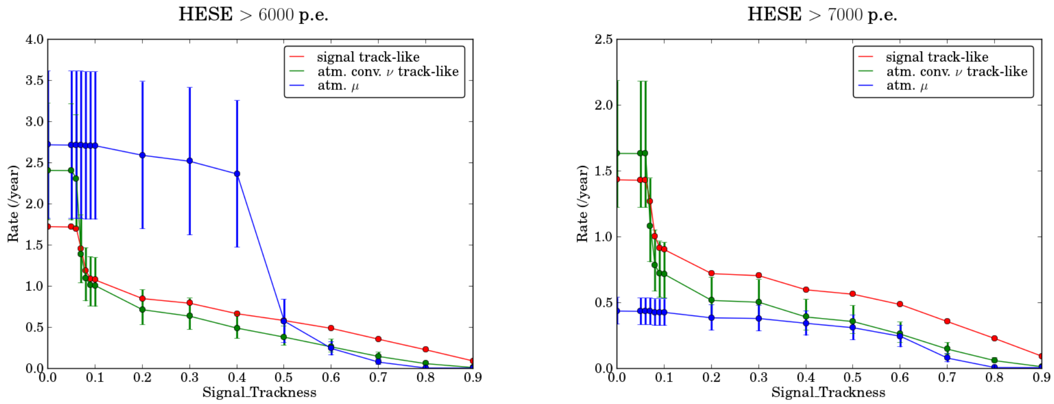
$$f_{\text{track}} = \frac{R_\mu R_{\mu,\text{cc}} + R_\tau R_{\tau,\text{cc}} R_{\tau,\text{cc},\mu}}{R_e + R_\mu + R_\tau}. \tag{2}$$

Here $R_e : R_\mu : R_\tau$ are 2.48 : 1.0 : 1.52, $R_{\mu,\text{cc}} = 0.78$, $R_{\tau,\text{cc}} = 0.86$ are fractions of ν_μ and ν_τ events interact via charged-current (CC), respectively, and $R_{\tau,\text{cc},\mu}$ is related to the branching ratio of $\tau \to \mu$ in Monte Carlo (Note that this number is approximately half of the $\tau \to \mu$ branching ratio of 0.18, because only about half of the $\tau \to \mu$ decays put enough energy into the muon for it to be detected as a high energy muon). The quantity $f_{\text{bkg}}/f_{\text{sig}}$ is the ratio of the background to signal event rate that is dependent on charge.

Based on our studies, for signal_trackness < 0.1 we can not well distinguish tracks from showers. **Therefore, we only send events having signal_trackness ≥ 0.1. This yields about 1.1 signal-like track-like events and about 3.7 background events per year.**

6 Options for Increasing the Signal-to-Noise Ratio

Each HESE alert contains quantities that can be used downstream of IceCube to increase the signal-to-noise ratio, at the expense of some signal efficiency. Requiring a larger signal trackness results in less background and less signal. One parameter that can be used to do this is signal_trackness. Figure 1(a) shows the rate versus different



(a) Charge > 6000 p.e. (b) Charge > 7000 p.e.

Figure 1: Rate (number of events per year) vs. different cuts on signal_trackness estimator for HESE signal and background with charge (a) > 6000 p.e. and (b) > 7000 p.e.: HESE track events are shown in red, the atmospheric conventional neutrinos in green, and the atmospheric muons in blue.

Table 2: Different cuts on event charges result in different signal and noise rates and signal to noise ratios.

Charge	Signal Rate (/yr) (R_s)	Background Rate (/yr) (R_b)	SNR $= \frac{R_s}{\sqrt{R_s+R_b}}$
6000	1.08	3.66	0.50
6500	0.99	2.74	0.51
7000	0.90	1.10	0.64
7500	0.83	0.87	0.64

cuts on signal_trackness for three event types: HESE track events in red, track-like atmospheric conventional neutrino background in green, and track-like atmospheric muon background in blue.

Another option is to require larger deposited charge. Table 2 shows the signal and background rates (expected number of events per year) for different charge cuts as well as the signal to noise ratio (SNR). All numbers in this table are for events with signal_trackness ≥ 0.1. The followup observatories can decide which events to image based on their charge, signal_trackness, and rate information.

Figure 1(b) shows the rate (number of events per year) vs. different cuts on signal_trackness for signal and background HESE with charge > 7000 p.e. In this figure, HESE track events are shown in red, the atmospheric conventional neutrino background in green, and the atmospheric muons in blue.

7 Angular Error

The simulation of HESE track events provides estimations of HESE angular errors in realtime. The angular separation between the true neutrino direction and online reconstructed direction is an estimate of how well our online reconstruction performs. Events with signal_trackness ≥ 0.1 have an angular error that varies between $0.4°$ and $1.6°$ (radius of the error-circle), 50% of the time (between $1.2°$ and $8.9°$ radius, 90% of the time) based on properties of the individual events in simulated HESE track samples.

We will issue a revision with a better angular error once we have run better reconstructions in the north.

8 Useful links

- AMON streams at GCN: `http://gcn.gsfc.nasa.gov/amon.html`
- GCN socket description of the HESE stream can be found on the GCN socket page (scroll down to "TYPE=158 PACKET CONTENTS"): `http://gcn.gsfc.nasa.gov/sock_pkt_def_doc.html`

References

[1] M.G. Aartsen et al., *Science* 342, 1242856, 2013.

[2] R. Abbasi et al., *PRL* 111, 021103, 2013.

[3] The IceCube Collaboration, *Proc. of the 34th Int. Cosmic Ray Conf.* 1081, 2015.